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Discussion Article

Comparative Life Cycle Assessment of Two Biofuels
Ethanol from Sugar Beet and Rapeseed Methyl Ester

With a Preface by Jörg Schweinle

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Preface: 'Biofuels' by Jörg Schweinle

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The mitigation of climate change is topic number one on the global agenda. Many countries that did sign the Kyoto Protocol obligated themselves to reduce GHG emissions by more or less remarkable amounts. The pre-2004 EU Member States (EU-15) 2008–2012 Kyoto target, for example, have cut greenhouse gas emissions to 8% below 1990 levels. For the year 2020, the target is set to 20% below 1990 levels for all EU-27 Member States.

What are the options to achieve these targets? Besides cutting energy consumption, increasing energy efficiency and carbon sequestration, the decarbonisation of energy supply by expansion of renewable energies is the main pillar for GHG reduction. While energy, industry, housing, and other sectors do have a variety of options, transport and especially the road transport sector so far has only one option to 'decarbonise' its energy consumption. That is the use of liquid biofuels. So far, the only economically viable feedstock for liquid biofuels is biomass. Bio-ethanol, the worldwide most important liquid biofuel – total production in 2005 ca. 35 billion litres – is produced mainly from sugar cane and corn, whereas biodiesel (RME) as the other important biofuel is mainly made of rapeseed, other oilseeds and, to a minor extent, of palm oil.

Three articles lately published in *Atmospheric Chemistry and Physics* as well as *Science*, however, question a net-decarbonisation or net-reduction of GHG emissions by the consumption of biomass based on liquid biofuels. Crutzen et al. (2008) consider N_2O emissions which are a by-product of N fertilisation in agriculture as one responsible factor to enhanced GHG emissions compared to consumption of fossil fuels. According to their calculations, Crutzen et al. doubt that the IPCC (2006) conversion factor of 1.45% for direct and indirect emissions from agricultural land for newly fixed N to N_2O-N is correct. Using a 'top-down' approach, they found an overall conversion factor of 3–5%. Fargione et al. (2008) as well as Searchinger et al. (2008) show that conversion of natural habitats for biofuel production can lead to remarkable carbon emissions that exceed total emissions of fossil fuels by far. Although the three papers are not based on empirical studies but on models (Crutzen et al., Searchinger et al.) or a meta-analysis (Fargione et al.), and the model calculations are based on a number of assumptions that could be critically discussed, the results should be reflected in LCA studies on biofuels and preferably other biomass-based products as well.

The following paper by Halleux et al. (2008), a comparative LCA of two biofuels produced in Belgium, was in the review process at the time as the paper by Crutzen et al. itself was first published as a discussion paper in 2007. Hence, a controversial, yet fruitful, discussion between authors and reviewers started on whether all relevant aspects were thoroughly addressed. The paper as it is published now is a result of this fruitful discussion. Since the topic is of high societal interest and results of scientific papers including LCA studies do very much support political decisions on biofuels and bio-energy, we would very much like to open this discussion and call for papers that address certain aspects of this topic.

Our feeling is that, although including different conversion factors of N to N_2O-N emissions are on first sight not a big issue, the conversion of natural habitats and its effects might be. To us, a few questions arise that need to be addressed: Is the carbon emission of land conversion to be fully allocated to biofuel production if a crop for food production is produced on the same site after one year? What if biofuels are produced on sites that have been converted 10 years ago? What if biofuel production competes with food production on scarce agricultural land and, hence, natural habitats are converted for food production. Are the carbon emissions of this land conversion to be allocated to biofuel production too? What about effects on biodiversity?

LCA methodology is challenged to faster integrate the results developed by the special disciplines.

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Abstract

Background, Aims and Scope. To all Member States, the European Union has imposed a minimum percentage of 2% of biofuels in the fuels consumed for road transport since 2005. This percentage is expected to reach 5.75% in 2010, and probably 10% in 2020. In this context, investments are made everywhere in Europe in local productions of biofuels. In Belgium, ethanol from sugar beet and rapeseed methyl ester (RME) are generally supposed to be two of the more valuable possibilities.
As these industries are growing, it is important to evaluate the environmental impacts of these productions and to highlight the main sources of these impacts using Life Cycle Assessment methodology. This evaluation will also lead to propositions of improvements of the environmental performances. A comparison with the impacts of the related fossil fuels (petrol and diesel) should also be conducted. Even if these fuels are different and used in different types of engines, it is important to determine which one offers the best environmental performances, as both require arable land, which is the limiting parameter in biofuel production.

Methods. The system boundaries include cultivation, extraction, processing and final use of the biofuels. The system has been expanded to take into account valorization of by-products in substitution of animal feed (rapeseed meal or pulps from sugar beet) or chemicals (glycerin). No economical, mass or energetic allocation was made. The yields and fertilizer consumptions of the crops are those of the Belgian conditions. Simapro 7.1 databases and the Eco-Indicator 99 method have been used for the Life Cycle Impact Assessment. The functional unit was road transport over 100 km.

Results. The results show that, without valorization of the by-products, the impacts of the two biofuels over their whole life cycle are not significantly lower than those of the related fossil fuels. However, the credits accorded thanks to the valorization of by-products lead to improvements of the environmental performances in comparison to fossil fuels, especially for RME.

Discussion. The impacts of agriculture and production of the fertilizers are more important in the case of RME, because the yield per hectare is lower than in the production of ethanol from sugar beet. However, the extraction of the sugar from the beet, fermentation, purification of the ethanol and drying of the pulps and slops consume much more energy than extraction and esterification of rapeseed oil. Moreover, the by-products of RME (rapeseed meal and glycerin) are more valuable than those of ethanol from sugar beet (pulps). This induces a more important environmental benefit in the production of RME. These parameters lead to a global environmental impact that is higher for the production of ethanol than for RME.

Conclusions. Life Cycle Assessment methodology has been successfully applied to two of the major ways of production of biofuels in Belgium using specific local data. The assessment of the environmental impacts reveals that rapeseed methyl ester allows a considerable improvement of the environmental performances compared to fossil diesel, while ethanol from sugar beet offers a more limited benefit compared to petrol.

Recommendations. Arable land is a limited resource, especially in West-European countries like Belgium. Therefore, choices must be made to have the most valuable environmental benefit. Soil quality and crop rotations should also be taken into account before making a decision.

Keywords: Biodiesel; biofuels; comparative LCA; ethanol; rapeseed; sugar beet

Introduction

Global warming and resource depletion are two priorities of the international environmental policy. Interest for renewable energy is growing and biofuels seem to bring a part of the solution to these two problems. A full substitution of fossil fuels isn't possible, as the production is limited by the availability of arable land, but using biofuels in a certain percentage as additives to fossil fuels should allow a reduction of the consumption of fossil fuels and emissions of greenhouse gases.

European directive 2003/30 [1] imposes to all Member States a minimum percentage of 2% of biofuel in the fuels consumed for road transport since 2005. This percentage is expected to reach 5.75% in 2010, and probably 10% in 2020. A few months ago, Belgium has accorded quotas to companies for a total annual production of 250 millions liters of bio-ethanol (from wheat or sugar beet) and 380 millions liters of bio-diesel (mainly rapeseed methyl ester) [2].

1 Goal Definition

The development of the biofuels industry in Europe has lead to a lot of environmental studies and today, energy and greenhouse gases balance over their whole life cycles is well known [3–5]. However, other environmental impacts, especially arable land use, have rarely been studied [6–8]. Moreover, by-products are often taken into account by allocating the impacts in function of their mass, energetic content or economical value [6,8]. A well-chosen allocation coefficient should offer a good estimation of the global environmental impact of a system, but it could also generate different results in some impact categories, as the benefit of a by-product can be high in some categories and low in others. This problem will be illustrated in the case of the 'acidification' and 'land use' impact categories for RME.

The aim of this study is to perform a full comparative Life Cycle Assessment of the production and use of two biofuels: Ethanol from sugar beet and rapeseed methyl ester. First of all, a comparison with the corresponding fossil fuels will show if these ways of producing biofuels really offer an environmental benefit. The second step will be a direct comparison of these two biofuels. This comparison is necessary, because their uses are similar (road transport in middle-size cars) and because productions of these fuels are in competition for arable land use, which is the limiting parameter. The last step will be the identification of the main sources of the environmental impacts and the proposition of improvements of the environmental performances.

2 Scope Definition

The system boundaries include the production (cultivation and processing for biofuels, extraction and refining for fossil fuels), but also the final use of the fuel and the valorization of the different by-products. This valorization is taken into account by subtracting the impacts of the production of the chemicals or animal feed, which these by-products substitute. An energetic valorization could be developed in the near future, but these two destinations are today the

solutions in place for these by-products. A quantitative description of the different included flows is given in the third paragraph.

The functional unit to which all emissions and consumptions in this assessment have been reported is 100 km covered with a middle-size and recent car. Even if biofuels are generally used as additives, results will be presented for cars working with pure biofuels as the mixing with fossil fuels could have an influence on the conclusions of the comparison and the aim is to determine which biofuel offers the highest environmental benefit.

The Eco-Indicator 99 method [9] has been used in this study. The relevant environmental impact categories are:

- Carcinogenic effects
- Inorganic respiratory effects
- Organic respiratory effects
- Global warming
- Ecotoxicity
- Acidification and eutrophication
- Fossil fuels

The chosen cultural perspective is the hierarchist one. Normalization factor is the impact of an average European person and weighting factors are 400 for human health, 400 for ecosystem quality and 200 for resources.

Arable land availability is limited and biofuels are in competition with food production, but the Eco-Indicator 99 method doesn't allow us to study this impact. The only possibility given in this method is the study of land conversion and loss of biodiversity, but arable land is not considered as a resource. As a consequence, land use will be studied qualitatively and separated from the other impacts.

3 Methodology and Life Cycle Inventory

3.1 Fossil fuels

The Life Cycle Inventory of the extraction, production, and distribution of the fossil fuels (petrol and diesel) has been established using the Simapro 7.1 databases [10]. The data for greenhouse gas emissions and fuel consumptions results from the comparison of different literature sources [5–7]. NO_X, VOC and particulate emissions from the car are calculated as the average emissions of middle-size cars from the Annual certification test results (2005) of the US Environmental Protection Agency [11]. The exhaust emissions and fuel consumptions of the petrol and the diesel cars are summarized in **Table 1**.

3.2 Biofuels

(1) Culture: The first step in the production of biofuels is the culture of rapeseed or sugar beet. The production of the fertilizers (N, P, K) and the pesticides, soils emission of N_2O, the consumptions and emissions of the tractors (fertilizing, tillage, sowing, harvesting, transport) and the valorization of by-products, like rapeseed straw or tops of sugar beet, substituting fertilizers (also in terms of N, P, K) for the next crop have been taken into account. The collected data, summarized in **Table 2** [3,4,6,12], comes from different sources to ensure the robustness of the study. The fertilizer consumptions in this table are net consumptions (the benefits of the straw or the tops are already subtracted). All transportation steps have also been taken into account. Priority has been accorded to Belgian and recent data for consumptions and yields of the crops.

Table 1: Energetic consumption and exhaust emissions of vehicles [11,14]

	Petrol	Diesel	Ethanol	RME
Consumption (MJ/100 km)	223,5	183,1	223,5	183,1
CO_2 (fossil) (kg/100 km)	16.6	13.4	–	0.74
CH_4 (mg/100 km)	2.4	7.6	2.4	7.6
N_2O (mg/100 km)	0.129	0.0645	0.129	0.0645
NO_X (mg/100 km)	10.2	25.6	6.35	28.2
Particulates (mg/100 km)	0.5	3.56	0.5	1.89
NMVOC (mg/100 km)	2.53	9.59	6.36	3.17

Table 2: Mass balance of the crops (kg/ha) [3,4,6,12]

	Rapeseed	Sugar beet
N fertilizer	144	135
K2O	74	212,5
P2O5	74	125
Pesticides	2.3	5.3
Fuel consumed	111.3	101
RME produced	1406	–
Ethanol produced	–	4104

Table 3: Mass and energy balance of RME production [6,12,13]

	Heat (MJ/ t RME)	Electricity (kWh/ t RME)	Chemicals (kg/t RME)	By-products (kg/t RME)
Drying	812	33	–	–
Extraction	2317	106	Hexane: 2.7	Meal: 1582
Refining	162	11	–	–
Esterification	947	37	Methanol: 109	Glycerin: 100

(2) Processing (RME): The next step is the conversion of the feedstock to biofuel. The energetic and chemical consumptions of the rapeseed process are summarized in **Table 3** [6,12,13]. After drying the rapeseed grains, oil is extracted in two steps, involving a mechanical extraction followed by an extraction with an organic solvent, generally hexane. This solvent is then separated and recycled, but a small quantity is lost (emission to air). Two products are generated: The oil, and the rapeseed meal, rich in proteins and easily integrated in rations of animal feed. The extracted oil is then refined, and finally reacts with fossil methanol to produce rapeseed methyl ester and glycerin, which is purified and then generally used in the chemical industry.

Table 4: Mass and energy balance of ethanol production [6,13]

	Heat (MJ/ t ethanol)	Electricity (kWh/ t ethanol)	By-products (kg/ t ethanol)
Washing and shredding	–	61	–
Sugar extraction	970	139	–
Fermentation	–	76	–
Purification	5271	50	–
Pulps and slops drying	5708	135	Pulps: 746

(3) **Processing (ethanol):** After washing and shredding the beets, sugar is extracted by diffusion. The syrup obtained is then pasteurized and fermented to produce an ethanol solution. Distillation and purification of this solution produces the ethanol fuel. The by-products of this process are the pulps and the slops, which are dried together and used for animal feed. The value of this feed is quite weak, due to the low content in proteins or sugar. Moreover, drying consumes a lot of energy, but that's the best destination for these products on economic grounds. Data is summarized in **Table 4** [6,13].

(4) **Final use:** The exhaust emissions and fuel consumptions of the vehicles have been calculated on the basis of those of the fossil fuel vehicles. Of course, the energetic contents of the biofuels are different from those of the corresponding fossil fuels and the consumptions, expressed in l/km, are different. However, the efficiencies of the motors, in MJ/km, and the greenhouse-gas emissions (g/km), with the exception of fossil carbon dioxide, are assumed to be the same for the biofuels and the corresponding fossil fuels [5–7]. As it belongs to the natural cycle of carbon, CO_2 emitted by the combustion of the biofuels doesn't contribute to global warming and is not taken into account, with the exception of a small part due to the combustion of fossil methanol in the case of biodiesel. Using ethanol leads to a decrease of the emissions of nitrogen oxides, an increase of the emissions of VOC and has no effect on the emissions of particulates [11]. Emissions of cars running on RME aren't given in the certification results of EPA, but another study of EPA reveals that the use of RME leads to a decrease of the emissions of particulates (47%) and VOC (67%), but also to an increase of the emissions of NO_X (10%) [14]. With these percentages and the emissions of fossil diesel, we have calculated emissions of a middle-size car running on RME. This is also summarized in Table 1.

Table 5: Protein, sugar and starch content of the animal feed [15–17]

	Proteins (%)	Sugar – Starch (%)
Rapeseed meal	35	32
Pulps and slops from sugar beet (dried)	11	12
Wheat	12	63
Protein peas	25	50

Table 6: Equivalencies of the by-products with reference animal feed

	Production (kg/ha)	Equivalent protein peas (kg/kg)	Equivalent wheat (kg/kg)
Rapeseed meal	2224	1.87	–0.97
Pulps from sugar beet (dried)	3060	0.58	–0.28

The complete Life Cycle Inventory has been established using Simapro 7.1 databases. By-products have been taken into account without energetic, mass or economic allocation. We have calculated environmental credits (avoided impacts of the production of equivalent products) for the substitution to other products like animal feed or chemical products. As no database was available for some of the by-products, we have made some assumptions to calculate equivalencies with some products described in the Simapro databases. The values of rapeseed meal and sugar beet pulps have been estimated in the function of their protein, sugar and starch contents (**Table 5**) [15,16,17] and then expressed in terms of equivalent combinations of protein peas and wheat (**Table 6**). Glycerin was assumed to substitute for the chemical glycerin, produced by hydrolysis of epichlorohydrin.

Life Cycle Impact Assessment was conducted using the Eco-Indicator 99 method, in the hierarchist perspective. First, we will present the characterization results, the results after normalization step and then the global environmental impacts after weighting.

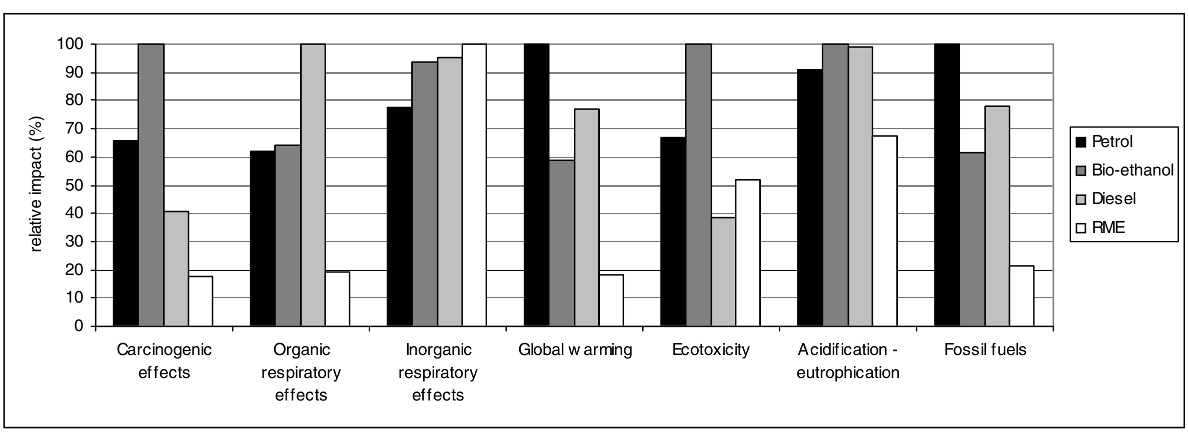

Fig. 1: Environmental impacts on a relative scale (characterization)

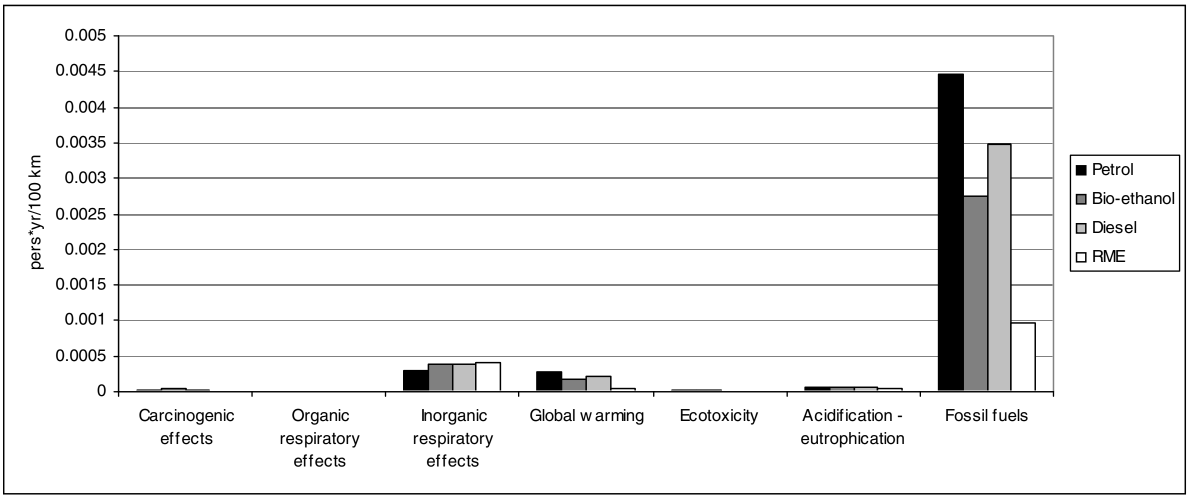

Fig. 2: Environmental impacts after normalization

4 Impact assessment

4.1 Characterization

Characterization results are presented on a relative scale on Biodiesel seems to be the system with the smallest impacts in all categories, except inorganic respiratory effects, due to the increase of the exhaust emissions of NO_X of the vehicle, and also in ecotoxicity, where fossil diesel has a smaller impact. Concerning bio-ethanol, the comparison with fossil fuels is more difficult, as it only offers improvements on global warming and fossil fuel consumption in comparison to petrol. Results after normalization will show which impact categories are the most important and comparison of the different systems will be easier.

4.2 After normalization step

The environmental impacts after normalization step are presented on **Fig. 2**.

We can see that the 'fossil fuels' category largely dominates all the others, and that RME is the fuel with the smallest fossil fuels consumption. This graph also shows that limiting a study to the categories 'fossil fuels' and 'global warming' could have important consequences on the conclusions. Some impacts on human health, especially respiratory effects, have to be taken into account.

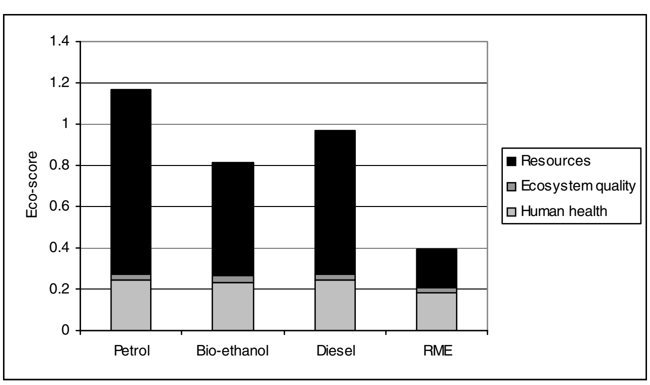

Fig. 3: Global environmental impacts after weighting

4.2 After weighting

The global environmental impacts after weighting show results that are easier to compare, but have to be interpreted with caution, due to their subjective aspect. These results are illustrated on **Fig. 3**.

From this figure, the benefit of RME is easily seen. Its weighted impact is almost half as high as that of bio-ethanol and the improvement in comparison to fossil diesel is 59%. Ethanol seems to offer a smaller benefit, with a reduction of the global impact of 30% in comparison to petrol.

4.3 Land use

The Eco-Indicator 99 method doesn't consider arable land as a limited resource. In this context, it wasn't possible to assess the impacts of land use and to compare them to other impacts after a normalization step. It would have been interesting to see if the addition of this impact to the others had led to a higher global impact for biofuels than to fossil fuels.

However, a qualitative comparison between the two biofuels is possible. The arable surface necessary to produce enough fuel to cover 100 km is more important in the case of RME, because the yield of the crop is lower than that of bio-ethanol. But the production of rapeseed meal allows one to avoid a production of animal feed that would have used an important quantity of arable land. This credit (equal to the surface that would have been used for the equivalent wheat and protein peas production) is a lot more important in the case of rapeseed meal than in the case of pulps of sugar beet. This leads to a higher global 'land consumption' for bio-ethanol. This is detailed in **Table 7**.

Table 7: Impact of land consumption (m²)

	'Land consumption' for 100 km	Credit by-products	'Global impact'
RME	35	29.5	5.5
Bio-ethanol	20.3	7.5	12.8

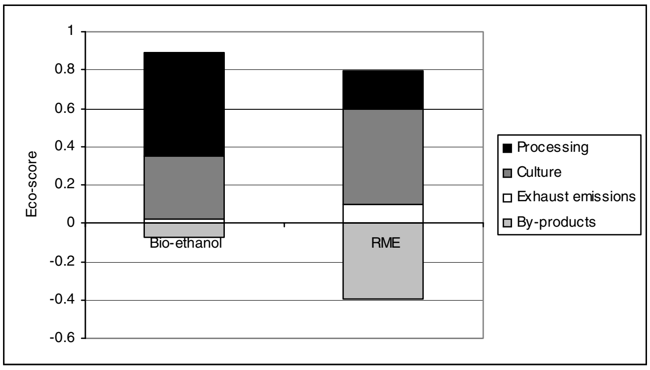

Fig. 4: Contributions to the global environmental impact

5 Conclusions and Discussion

5.1 Sources of the impacts

In order to improve the performances of the systems, we will now emphasize the main sources of the environmental impacts, by dividing the weighted impact into four sections: the culture, the processing, the exhaust emissions of the motor, and finally the credit offered by the valorization of the by-products (**Fig. 4**).

The first observation on the graphs is that without a valorization of the by-products, RME has a higher global environmental impact, almost equal to that of bio-ethanol and that of the improvements in comparison to fossil fuels (whose impacts were presented in Fig. 2) would respectively be 18% for biodiesel and 24% for bio-ethanol. But rapeseed meal and glycerin are valuable products, the first in animal feed and the second in the chemical industry. They offer an important environmental credit, which is not the case for sugar beet pulps.

The majority of impacts of RME come from the culture. The yield of the crop is quite low in comparison to bio-ethanol, so the impacts of the production of fertilizers and the working of the tractors and agricultural machines are divided by a smaller quantity of biofuel. This explains why the impact of the culture is more important for RME than for ethanol. However, the impact of the processing is lower for RME. The extraction of the oil from the grains is easier than extraction of sugar, fermentation and distillation of the ethanol. These two parameters lead to global impacts that are almost similar for the two biofuels without valorization of the by-products.

5.2 Allocation coefficient

As the importance of by-products of the RME industry has been showed, it would be interesting to calculate which allocation coefficients would have lead to the same conclusions. **Table 8** gives the global environmental impact after weighting

Table 8: Equivalent allocation coefficients

	Global environmental impact without any valorization (Millipoint/100km)	Environmental credit offered (Millipoint/100 km)	Equivalent allocation coefficient (%)
Rapeseed meal	0.792	–0.289	36.5
Glycerin		–0.108	13.6

Table 9: Details of the acidification category

	Fossil diesel	RME	RME without valorization of rapeseed meal	RME using an allocation coefficient of 36%
Weighted impact for acidification (Millipoint)	0.025	0.017	0.053	0.034

of the use of RME without valorization of rapeseed meal and glycerin, the credit that is offered by these two products, and finally the equivalent allocation coefficients.

The calculated coefficient for rapeseed meal is similar to the allocation coefficient suggested in other studies [12].

5.3 Comparison with other studies

The energy and greenhouse gas balances of the two biofuels are similar to those obtained by former studies [8,18]. The main difference between our results and these studies concerns the impact of biodiesel on acidification, which they found to be more important than that of fossil diesel. It is interesting to notice that we would also have come to their conclusion if an allocation had been applied to take into account the effects of the valorization of rapeseed meal. Effectively, while glycerin only offers a small benefit in this impact category, rapeseed meal's benefit is here proportionally higher than its global benefit after weighting. This is shown in **Table 9**.

In the same way, if the allocation coefficient had been used to study the impact of land use, we would have come to another conclusion, as the benefit of rapeseed meal is also largely higher than 36% in this category. Using a lower allocation coefficient than 36%, as is done in [6], the impacts of RME on 'land use' and 'acidification' would of course have been even more important.

This illustrates the importance of avoiding allocation when possible, as the choice of a coefficient potentially affects some conclusions of the study.

6 Recommendations

The production of biofuels allows an improvement of the environmental impacts in comparison to fossil fuels. However, impacts are still considerable, especially for ethanol from sugar beet, where improvements should be made to reduce the energetic consumption of the processing.

The impacts of arable land consumption have only been taken into account qualitatively, but once again, RME had a lower impact than bio-ethanol. The addition of this impact to the other environmental impacts would have been unfavorable to the two biofuels in comparison to fossil fuels and could have changed the conclusions of this study. A way of evaluating the impacts of land occupation quantitatively and, in addition to other environmental impacts, should be developed in the future Life Cycle Impact Assessment methods.

Finally, it should be remembered that this study only highlights the environmental aspects of biofuel production. Socio-economic parameters should also be taken into account before choosing which way to promote [19,20, see also 21,22].

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Goal and Scope. The environmental performance of two ethanol fuel applications (E10 and E85) is compared (E10 fuel: a mixture of 10% ethanol and 90% gasoline by volume, and E85 fuel: a mixture of 85% ethanol and 15% gasoline by volume).

Methods. Two types of functional units are considered here: An ethanol production-oriented perspective and a traveling distance-oriented perspective. The ethanol production-oriented functional unit perspective reflects the fact that the ethanol fuel supply (arable land or quantity of biomass used in ethanol fuel) is constrained, while the traveling distance-oriented functional unit implies that the ethanol fuel supply is unlimited.

Results and Discussion. In the ethanol production-oriented functional unit perspective, the E10 fuel application offers better environmental performance than the E85 fuel application in terms of natural resources used, nonrenewable energy and global warming. However, in the calculations based on the traveling distance perspective, the E85 fuel application provides less environmental impacts in crude oil consumption, nonrenewable energy and global warming than the E10 fuel application.

Conclusions and Outlook. The choice of functional units significantly affects the final results. Thus the functional unit in a descriptive LCA should reflect as nearly as possible the actual situation associated with a product system. Considering the current situation of constrained ethanol fuel supply, the E10 fuel application offers better environmental performance in natural resources used, nonrenewable energy and global warming unless the fuel economy of an E85 fueled vehicle is close to that of an E10 fueled vehicle.